

## **Engineering Geological Characteristics and Slope Stability of a Road-Cut Excavated in Serpentine Mélange, Aceh Besar, Indonesia**

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**Abstract:** Road-cut slopes excavated in serpentinite mélange are highly susceptible to landslides because of the weak engineering properties of the rock mass, extensive weathering, and intense tectonic deformation. This study aims to investigate the engineering geological characteristics and slope stability of a road-cut excavated through serpentinite mélange in Aceh Besar, Indonesia. Field investigations were conducted to characterize the lithology, weathering conditions, rock mass quality, discontinuity characteristics, and evidence of slope instability. Geological observations were integrated with engineering geological assessments to identify the primary factors controlling slope failure. The investigated slope consists predominantly of highly weathered serpentinite mélange characterized by a heterogeneous rock mass, pervasive fracturing, and a weak serpentinitic matrix. The road excavation has significantly modified the natural slope geometry by increasing the slope angle and removing lateral support, thereby reducing slope stability. Field observations revealed loose rock fragments, localized erosion, detached blocks, and tension cracks, indicating progressive slope deterioration. Rainfall infiltration through discontinuities and weathered zones is interpreted as the principal triggering factor, whereas the weak lithology, advanced weathering, and abundant structural discontinuities constitute the primary predisposing factors. The dominant failure mechanisms are interpreted as rockfall and shallow translational sliding. The results demonstrate that serpentinite mélange represents a high-risk geological material for road construction in mountainous areas. Comprehensive engineering geological investigations, appropriate slope design, effective drainage systems, and stabilization measures are therefore essential to reduce landslide hazards and ensure the long-term stability of road infrastructure developed within serpentinite mélange terrains.

**Keywords:** Serpentinite Mélange; Road-Cut Slope; Landslide; Engineering Geology; Slope Stability; Aceh Besar.

### **INTRODUCTION**

Landslides are among the most destructive geological hazards worldwide, causing significant economic losses, damage to infrastructure, and fatalities every year. The occurrence of landslides is controlled by the interaction of geological, geomorphological, hydrological, and anthropogenic factors. Among these, road construction in mountainous terrains has become one of the most important human activities that alter natural slope equilibrium by removing lateral support, increasing slope inclination, and exposing weathered rock masses to surface processes. Consequently, road-cut slopes commonly experience instability, particularly during periods of intense rainfall when pore-water pressure increases and shear strength decreases (Cruden & Varnes, 1996; Turner & Schuster, 1996).

The geological characteristics of the slope material play a fundamental role in determining slope stability. Weak, highly fractured, and intensely weathered rocks generally exhibit lower shear strength than intact crystalline rocks, making them more susceptible to failure. Among these lithologies, serpentinite and serpentinite mélange are widely recognized as engineering geological materials with poor mechanical properties because they commonly contain numerous discontinuities, shear zones, and alteration minerals that reduce rock mass strength (Aydan, 1989; Hearn et al., 1995). These characteristics become more critical when large road cuts are constructed without adequate slope stabilization measures.

Serpentinite is formed through the hydrothermal alteration of ultramafic rocks such as peridotite and dunite, producing serpentine minerals dominated by lizardite, chrysotile, and antigorite (Evans, 2004). During serpentinization, olivine and pyroxene are replaced by serpentine minerals accompanied by the formation of magnetite and brucite. This mineralogical transformation significantly modifies the physical and mechanical properties of the original ultramafic rocks by reducing density, increasing porosity, and decreasing rock strength

(O'Hanley, 1996). As weathering progresses, serpentinite becomes increasingly friable and susceptible to erosion and slope failure.

Serpentinite mélange represents an even more complex geological unit. *Mélanges* are tectonically disrupted rock bodies composed of blocks of various lithologies embedded within a highly sheared matrix formed during subduction and accretionary processes (Raymond, 1984). In many subduction complexes, serpentinite acts as the matrix material that encloses blocks of sandstone, limestone, basalt, chert, and metamorphic rocks. The resulting heterogeneous rock mass is characterized by irregular block distribution, pervasive fracturing, intense shearing, and variable weathering intensity. Such geological complexity produces highly anisotropic mechanical behavior and makes prediction of slope performance particularly challenging (Festa et al., 2019).

From an engineering geological perspective, serpentinite mélange poses considerable challenges because failure surfaces often develop along pre-existing shear zones, weathered serpentinite, or contacts between competent blocks and the weak matrix. Rainwater infiltration further accelerates weathering and elevates pore-water pressure within the fractured rock mass, thereby reducing effective stress and shear resistance. Consequently, landslides occurring in serpentinite mélange are commonly classified as shallow slides, translational slides, debris slides, or rockfalls depending on local geological conditions and slope geometry (Hungr et al., 2014).

Indonesia is situated along the active Sunda convergent margin where numerous accretionary complexes containing serpentinite mélange are exposed. In Aceh Province, northern Sumatra, serpentinite mélange crops out extensively within the Indrapuri Complex and adjacent tectonic belts. These rocks have experienced multiple phases of deformation associated with subduction, collision, and strike-slip faulting, resulting in highly fractured and weathered rock masses. Several transportation corridors have been developed across these geological units to improve regional accessibility. However, slope failures frequently occur along road cuts, especially during the rainy season, causing road closures, increased maintenance costs, and safety hazards for road users.

Despite the engineering significance of these failures, relatively few studies have documented the geological characteristics and instability mechanisms of road-cut slopes developed specifically in serpentinite mélange in Aceh. Most previous studies have focused on regional tectonics, petrology, and geochemistry of ultramafic rocks, whereas engineering geological aspects related to slope stability remain poorly understood. Detailed field observations of slope geometry, weathering characteristics, discontinuity patterns, and failure mechanisms are therefore essential to improve hazard assessment and slope management in serpentinite terrains.

The investigated road-cut slope provides an excellent opportunity to examine the engineering geological behavior of highly weathered serpentinite mélange exposed by road excavation. The slope exhibits extensive weathering, abundant discontinuities, heterogeneous rock fabrics, and evidence of progressive degradation that collectively influence its stability. Understanding these characteristics is important not only for evaluating present slope conditions but also for developing appropriate mitigation strategies for future infrastructure projects in similar geological environments.

Therefore, the objectives of this study are (1) to describe the geological and engineering characteristics of a road-cut slope developed in serpentinite mélange, (2) to identify the principal factors controlling slope instability, including lithology, weathering, discontinuity conditions, and slope geometry, and (3) to discuss the implications of these findings for landslide hazard mitigation and slope stabilization in serpentinite mélange terrains. The results are expected to contribute to a better understanding of slope behavior in weak tectonic *mélanges*.

and provide practical information for engineering geological investigations in similar accretionary complexes.

## **METHODS**

### **Study Area**

The investigated road-cut slope is located in Siron Krueng village, Aceh Besar Regency, Aceh Province, Indonesia. The slope was excavated to facilitate road construction through mountainous terrain dominated by serpentinite mélange of the Indrapuri Complex. The area is characterized by rugged topography with steep hillslopes and dense tropical vegetation. The regional climate is humid tropical, with annual rainfall exceeding 2,500 mm, which promotes intensive weathering and frequent landslide occurrences.

The investigated slope represents an artificial excavation that exposes highly weathered serpentinite mélange. The exposed rock mass displays variable degrees of weathering, abundant discontinuities, and heterogeneous lithological characteristics, making it suitable for evaluating the engineering geological conditions controlling slope instability.

### **Field Investigation**

Field investigations were conducted to characterize the geological and engineering properties of the road-cut slope. Geological mapping included observations of lithology, weathering grade, structural discontinuities, groundwater conditions, and evidence of previous slope failures. Particular attention was given to identifying discontinuity orientations, joint spacing, persistence, aperture, and infilling materials because these features strongly influence rock mass stability.

Slope geometry was documented by measuring slope height, slope angle, bench configuration (if present), and surface drainage conditions. The occurrence of tension cracks, loose rock blocks, erosion features, and rockfall deposits was also recorded. Representative photographs were taken to document the overall slope condition and failure characteristics.

Representative rock samples were collected from both relatively fresh and weathered serpentinite exposures for laboratory analysis. Sampling locations were selected to represent the dominant lithological characteristics observed along the road-cut exposure.

### **Engineering Geological Assessment**

The engineering geological condition of the slope was evaluated based on field observations of rock mass quality, weathering intensity, discontinuity characteristics, and slope morphology. The weathering degree was classified following the recommendations of the International Society for Rock Mechanics (ISRM, 2007).

Potential failure mechanisms were interpreted by integrating geological observations with slope geometry and discontinuity patterns. Possible failure types were classified according to the updated landslide classification proposed by Hungr et al. (2014), including rockfall, translational slide, rotational slide, and debris slide.

Although no numerical stability analysis was performed in this study, qualitative assessment was undertaken to identify the dominant factors controlling slope instability. These factors include lithology, degree of weathering, discontinuity density, groundwater infiltration, rainfall influence, and slope excavation associated with road construction.

### **Data Interpretation**

The collected field and laboratory data were integrated to evaluate the relationship between serpentinite mélange characteristics and landslide susceptibility. Geological observations were compared with laboratory results to determine how weathering, mineralogical alteration, and structural discontinuities affect slope stability.

The interpretation focused on identifying the dominant geological controls responsible for slope failure and discussing their implications for future road construction and slope stabilization in serpentinite mélange terrains.

## RESULTS AND DISCUSSION

### Slope Morphology



*Figure 1 Field photograph of the investigated road-cut slope exposing highly weathered serpentinite mélange characterized by extensive fracturing, heterogeneous rock mass, and steep excavation geometry.*

The investigated road-cut slope was excavated to accommodate road construction through mountainous terrain underlain by serpentinite mélange. The excavation produced a steep artificial slope with a considerable vertical height (Figure 2). No engineered stabilization measures, such as benches, retaining walls, rock bolts, or wire mesh, were observed along the exposed slope.

The upper part of the slope is covered by a thin layer of reddish residual soil, whereas the lower section exposes highly weathered serpentinite mélange. The slope surface is generally irregular and exhibits evidence of weathering, erosion, and localized rock fragmentation. Loose rock fragments have accumulated at the toe of the slope, indicating ongoing degradation of the exposed rock mass.

#### 1. Lithological Characteristics



*Figure 2 Road-cut slope excavated through highly weathered serpentinite mélange, showing steep slope geometry, intense weathering, and fractured rock mass conditions.*

The road cut exposes serpentinite mélange belonging to the Indrapuri Complex. The exposed rock mass consists predominantly of highly weathered serpentinite forming the matrix, with isolated blocks of more competent lithologies embedded within it.

The serpentinite exhibits greenish-grey to dark grey colours on relatively fresh surfaces but changes to brownish-yellow under weathered conditions. Intensive serpentinitization has almost completely replaced the original ultramafic minerals with serpentine minerals. Weathering has further altered the rock into a friable material that can be easily broken by hand in several parts of the slope.

The mélange exhibits a heterogeneous texture characterized by irregular block distribution and strongly sheared serpentinitic matrix. This heterogeneity produces significant variability in rock mass quality over short distances.

### **Rock Mass Condition**

Field observations indicate that the serpentinite mélange is intensely fractured and highly weathered. Numerous discontinuities, including joints, fractures, and shear surfaces, divide the rock mass into blocks of variable size. The discontinuities exhibit close spacing and high persistence, resulting in a fragmented rock mass with poor structural integrity. Several discontinuities are filled with weathered clay-rich materials derived from serpentinitization and subsequent chemical weathering. The combination of extensive fracturing and advanced weathering substantially reduces the mechanical competence of the rock mass and facilitates water infiltration into the slope.

### **Weathering Characteristics**

Weathering is one of the most prominent characteristics observed within the investigated slope. According to the ISRM weathering classification, most of the exposed serpentinite can be classified as highly weathered to completely weathered. Chemical weathering has transformed much of the original serpentinite into soft residual material rich

in clay minerals. Weathering is particularly intense near the ground surface and along discontinuities where groundwater circulation is concentrated. The progressive deterioration of the rock mass has reduced its strength and increased the likelihood of slope failure under external loading, particularly during periods of heavy rainfall.

### **Evidence of Slope Instability**

Several indicators of active slope instability were identified during the field investigation. These include loose rock fragments at the slope toe, localized erosion, detached blocks, and small-scale rockfalls. Although no large landslide scar was observed during the survey, the slope displays progressive deterioration associated with ongoing weathering and gravitational processes. Minor tension cracks are locally developed near the crest of the slope, while several detached blocks remain partially supported by adjacent fractured rock. These conditions indicate that the slope continues to evolve and may experience future failures if weathering and rainfall persist.

### **Preliminary Failure Mechanism**

Based on field observations, the dominant instability mechanisms are interpreted to include rockfall, shallow translational sliding, and localized debris sliding. These failures are primarily controlled by the interaction between steep slope geometry, highly weathered serpentinite, abundant discontinuities, and rainfall infiltration. Water entering the fractured rock mass is expected to increase pore-water pressure and reduce effective stress along discontinuities, thereby promoting block detachment and shallow slope failures. The absence of drainage facilities and slope protection measures further contributes to instability. Overall, the investigated slope exhibits geological and engineering characteristics that indicate moderate to high susceptibility to future landslide activity, particularly during prolonged rainfall events.

## **Discussion**

### **Influence of Serpentine Mélange on Slope Stability**

The field observations demonstrate that serpentinite mélange plays a fundamental role in controlling the instability of the investigated road-cut slope. Unlike massive crystalline rocks, serpentinite mélange consists of a heterogeneous assemblage of competent rock blocks enclosed within a weak and highly sheared serpentinitic matrix. This heterogeneous structure produces significant contrasts in mechanical properties and creates numerous discontinuities that reduce the overall strength of the rock mass (Raymond, 1984; Festa et al., 2019).

Serpentinization has profoundly altered the original ultramafic rocks by replacing olivine and pyroxene with serpentine minerals. This mineralogical transformation reduces rock density and strength while increasing the susceptibility of the rock mass to weathering and deformation (Evans, 2004; O'Hanley, 1996). Consequently, the exposed serpentinite becomes progressively weaker as weathering advances, promoting the formation of unstable slopes following excavation.

The investigated slope exhibits extensive weathering and pervasive fracturing, both of which significantly decrease rock mass quality. The abundance of discontinuities facilitates block detachment and provides preferential pathways for groundwater infiltration. Similar engineering geological characteristics have been reported for serpentinite slopes in Japan, Turkey, Taiwan, and California, where landslides frequently develop along weathered serpentinite and tectonic shear zones (Aydan, 1989; Hearn et al., 1995).

### **Effect of Road Excavation on Slope Failure**

The instability observed at the study site is closely associated with anthropogenic

modification of the natural slope. Prior to excavation, the hillside was in a relatively stable geomorphic condition. Road construction required removal of the lower part of the slope, thereby eliminating natural lateral support and increasing the slope angle beyond its long-term equilibrium.

Excavation also exposed fresh discontinuities to atmospheric weathering. Continuous exposure to rainfall and temperature fluctuations accelerated the degradation of the serpentinite, particularly along fractures and shear zones. The absence of benches and engineered stabilization measures further increased the susceptibility of the slope to failure.

These observations agree with previous studies indicating that road-cut slopes constructed in weak geological formations commonly experience progressive deterioration following excavation. Failure often initiates at localized discontinuities before propagating into larger slope movements as weathering and rainfall continue to reduce rock strength (Turner & Schuster, 1996).

### **Weathering and Rainfall as Triggering Factors**

Although lithology controls the inherent weakness of the slope, rainfall acts as the principal triggering mechanism for landslide occurrence. Serpentine mélange is characterized by abundant fractures and highly weathered zones that readily absorb infiltrating water.

During prolonged rainfall, water infiltrates through joints and fractures, increasing pore-water pressure while reducing effective stress along discontinuity surfaces. Simultaneously, weathered serpentinite undergoes softening, resulting in a substantial reduction in shear strength. These processes promote shallow translational sliding, debris sliding, and rockfall, particularly on steep artificial slopes.

The tropical climate of Aceh, with annual rainfall exceeding 2,500 mm, further accelerates chemical weathering. Continuous cycles of wetting and drying gradually weaken the exposed rock mass, leading to progressive deterioration even in the absence of major rainfall events. Therefore, rainfall should be considered the immediate triggering factor, whereas serpentinite mélange represents the fundamental predisposing geological condition.

### **Failure Mechanism**

Based on field observations, the investigated slope is interpreted to fail through a combination of rockfall and shallow translational sliding. The closely spaced discontinuities divide the rock mass into numerous unstable blocks that gradually detach under gravitational forces.

Highly weathered serpentinite located near the slope surface may also fail as debris slides during heavy rainfall because weathering transforms the rock into clay-rich residual soil with low shear strength. The interaction between steep slope geometry, weak serpentinite matrix, and intensive rainfall therefore produces a progressive failure mechanism rather than a single catastrophic collapse.

The observed failure mechanism is consistent with engineering geological models proposed for highly weathered serpentinite slopes, where failure commonly initiates along pre-existing discontinuities before developing into larger slope failures under unfavorable hydrological conditions (Hung et al., 2014).

### **Implications for Slope Management**

The findings of this study have important implications for infrastructure development in serpentinite mélange terrains. Conventional slope excavation methods may not provide adequate long-term stability where highly weathered serpentinite is present. Geological investigations should therefore be conducted prior to road construction to identify weak zones, discontinuity orientations, groundwater conditions, and weathering intensity.

Appropriate stabilization measures should include optimized slope geometry, bench construction, surface and subsurface drainage systems, rockfall protection, and revegetation to minimize erosion. Where discontinuities are abundant, additional reinforcement such as rock bolts, shotcrete, or retaining structures may be required to improve slope stability.

Regular monitoring during the rainy season is also recommended because progressive weathering and groundwater infiltration may gradually reduce slope stability over time. Early identification of tension cracks, rockfall activity, and localized erosion can significantly reduce landslide risk and improve road safety.

## CONCLUSION

This study investigated the geological and engineering characteristics of a road-cut slope excavated through serpentinite mélange in Aceh Besar, Indonesia. Field observations indicate that the exposed slope consists of highly weathered and intensely fractured serpentinite mélange with poor rock mass quality. The heterogeneous nature of the mélange, characterized by competent rock blocks embedded within a weak serpentinitic matrix, significantly reduces the mechanical stability of the slope.

The excavation of the road cut has modified the natural slope geometry by increasing the slope angle and removing lateral support. Combined with advanced weathering and abundant discontinuities, these conditions have created a highly unstable slope. Field evidence, including loose rock fragments, localized erosion, detached blocks, and tension cracks, indicates that the slope is undergoing progressive deterioration and remains susceptible to future failure.

Rainfall is interpreted as the primary triggering factor for slope instability. Water infiltration through fractures and weathered zones increases pore-water pressure and decreases the shear strength of the serpentinite, thereby promoting rockfalls and shallow translational slides. The interaction between weak lithology, intense weathering, structural discontinuities, steep slope geometry, and tropical rainfall collectively governs the landslide mechanism in the study area.

The findings emphasize that serpentinite mélange should be recognized as a high-risk geological material for road construction. Comprehensive engineering geological investigations should be conducted prior to excavation to identify weak zones, evaluate discontinuity conditions, and assess weathering intensity. Appropriate mitigation measures, including optimized slope geometry, effective drainage systems, bench construction, and slope reinforcement, are essential to improve long-term slope stability and reduce landslide hazards.

Future studies are recommended to incorporate quantitative slope stability analyses, detailed discontinuity measurements, hydrogeological investigations, and laboratory testing of the mechanical properties of serpentinite mélange. Such investigations will improve the understanding of slope behavior and support the development of more effective mitigation strategies for infrastructure constructed in serpentinite-dominated terrains.

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